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New Results in Charm Meson Spectroscopy from FOCUS and SELEX

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Abstract. I will review recent results in charmed meson spectroscopy from the Fermilab fixed target charm photo-production and hadro-production experiments, FOCUS and SELEX. FOCUS reports new measurements of the masses and widths of the D_2^{*+} and D_2^{*} mesons, evidence for D_0^{*+} and D_0^{*} broad states and a confirming observation of the $\mathrm{D}_{\mathrm{sJ}}^{+}(2317)$ and other recently observed high mass $\mathrm{D}_{\mathrm{sJ}}^{+}$ states. SELEX has recently reported evidence for a new $\mathrm{D}_{\mathrm{sJ}}^{+}(2632)$ state in both the $\mathrm{D}_{\mathrm{s}}^{+}\eta^0$ and $\mathrm{D}^0\mathrm{K}^+$ final states.

1. Introduction

The heavy-light meson systems are a unique laboratory for the study of hadronic structure. These systems are analogs of the hydrogen atom with a light spin $\frac{1}{2}$ quark bound to a heavy spin $\frac{1}{2}$ quark playing the roles of the electron and proton in hydrogen. Some of the hydrogen atom's lore carries over; the nuclear (heavy quark) spin should largely decouple from the problem. But the binding force is strong, not electromagnetic and decay is dominated by pseudo-scaler meson emission as well as vector photon decay. In the 'onia' systems j/ψ and Υ, the analogs of positronium, potential models are very successful in predicting the spectra and properties of the states; in these heavy-light systems similar models are only a starting point in understanding the physics.

In the charm system there are three such families of states; $\mathrm{D}^0(\mathrm{c\overline{u}})$, $\mathrm{D}^+(\mathrm{c\overline{d}})$ and, $\mathrm{D}_{\mathrm{s}}^{+}(\mathrm{c\overline{s}})$. Figure 1 shows the expected level structure for the lowest orbital angular momentum $\mathrm{L} = 0$ and $\mathrm{L} = 1$ states. There are four $\mathrm{L} = 1$ $\mathrm{D_J}, \mathrm{J} = \{0, 1, 1, 2\}$ states expected. The two of lowest J are expected to decay rapidly to the pair of $\mathrm{L} = 0$ ground states by pion emission, leading to broad states while the two with higher J are suppressed by centrifugal barriers and are expected to yield narrow states.

This picture was called into question in 2003 with the observation by BABAR [1] of a third narrow state in the D_s^+ system in the mode $\mathrm{D}_{\mathrm{sJ}}^{+}(2317) \to \mathrm{D}_{\mathrm{s}}^{+}\pi^0$. This state was confirmed and its narrow partner $\mathrm{D}_{\mathrm{sJ}}^{+}(2460) \to \mathrm{D}_{\mathrm{s}}^{*+}\pi^0$ was first observed by CLEO [2] shortly after BABAR's announcement. This left four narrow $\mathrm{D_s}$ states. It was quickly understood that these states were so low in mass that the $\mathrm{D}_{\mathrm{s}}^{+} \to \mathrm{DK}$ channels were closed leaving only isospin violating π^0 and photon final states open. The isospin violation kept these states narrow so the question became "why did potential and other models put their masses so high?".

In the non-strange D meson systems two narrow $\mathrm{L} = 1$ states have long been known. There is no evidence for additional narrow states. But can the broad states be seen and measured? FOCUS has made a large step toward answering these questions in the past year.

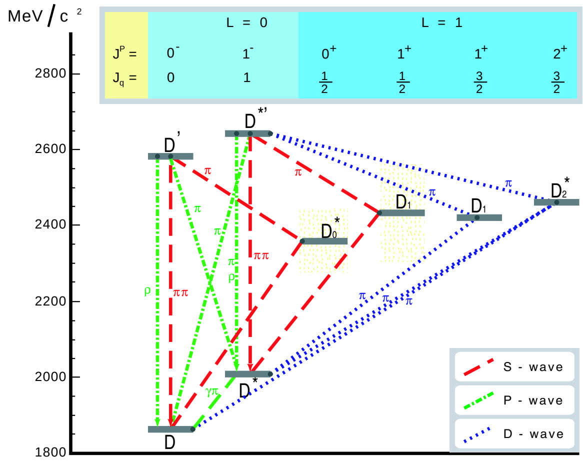

Figure 1. Expected levels and transitions for the L = 0 and L = 1 D_J states.

In D_s system we've found all four states expected, albeit all narrow when we expected two of them to be broad and higher in mass. SELEX has evidence for a fifth narrow state decaying mainly to $D_{sJ}^+(2632) \to D_s^+\eta^0$ at a high enough mass that the D^0K^+ channel is open and seen. This observation calls into question the assignments of all these states. Where does a fifth narrow state come from? What are its quantum numbers and internal structure? Are there tetraquarks or other exotica being seen in this system as have been suggested by some recent papers or are more conventional spectroscopic explanations sufficient [3, 4, 5, 6, 7, 8, 9]? Whichever it is a lively discussion in the literature has begun.

2. Experiments

FOCUS and SELEX are fixed target charm production and decay experiments which took data near the end of the Fermilab 800 GeV/c^2 fixed target program in 1996-7. FOCUS [10] was a charm photo-production experiment in a $< E_\gamma >\sim 200$ GeV/c^2 wideband photon beam. The experiment was an upgrade of the original E687. It exploited the relatively large fraction of charm produced in photo-production to yield very large samples of clean and well measured charmed mesons. In the usual all charged final states FOCUS has $\sim$ 1M fully reconstructed charmed mesons.

SELEX [11] is a charmed hadro-production experiment in a hyperon beam with acceptance in the forward direction $0.1 < x_F < 1.0$. Most data were taken with a 600 GeV/c^2 Σ^- beam. Our main goals were to study the production and decay properties of charmed baryons with an emphasis on the strange-charmed baryons where samples are still quite small. The charm fraction in hadro-production is much less than in photo-production and the mean charged multiplicity considerably higher. However the strange baryon beam enhances the production of charmed baryon and strange-charmed baryons relative to charmed mesons.

While the beams of these two experiments are quite different the experiments are rather similar. Each had thin targets and a high precision Silicon strip micro-vertex detectors to separate and measure secondary vertices from charm decays down to a fraction of the lifetimes of the shortest lived charmed baryons ($\sigma_\tau \sim 20$ fsec). Each experiment has excellent particle identification, FOCUS with multi-cell threshold Cherenkov counters and SELEX with a RICH. Each measured photons with lead glass arrays and secondary charged particles with conventional MWPC and drift chamber magnetic spectrometers.

3. FOCUS Results

FOCUS has exploited their large and well measured D meson data-set in order to simultaneously fit for the properties of the the broad and narrow L = 1 excited states in both the charged and neutral D systems. This is complicated analysis involving careful attention to feed-down, partially reconstructed states, etc. Likewise the fitting is delicate an therefore very carefully done. I cannot do justice to this work is the space available here. The reader is referred to FOCUS's publication [12] for the details.

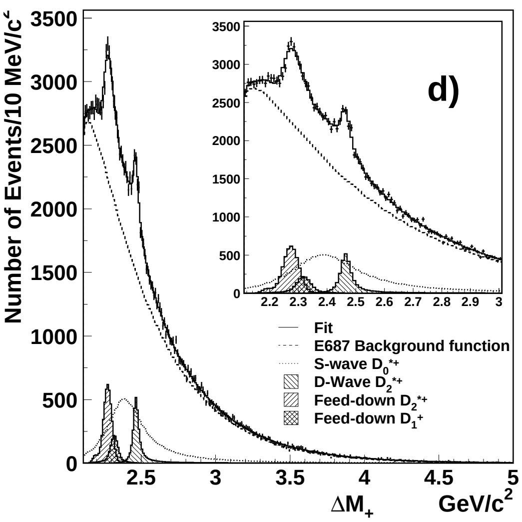

Figure 2. FOCUS data set with final fits for final state $D^0\pi^+$

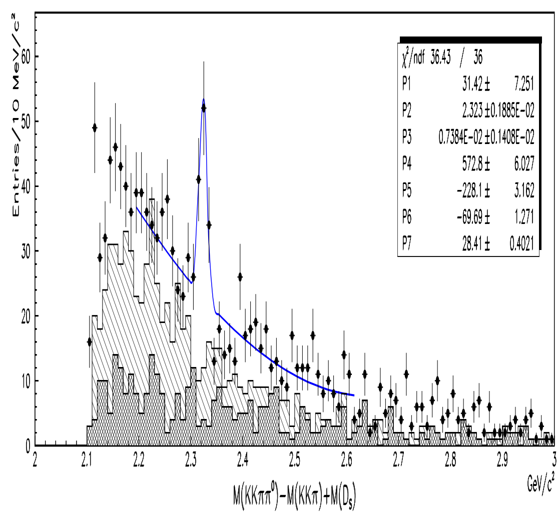

Figure 3. FOCUS $D_{sJ}^+(2317)$ signal

The character of data set and the final fits for the charged final state $D^0\pi^+$ are shown in Figure 2. The inclusion of the broad states into the fits improves the fit quality from unacceptable (χ^2/ndof ~ 3) to fine (confidence level 28%). The fit for the $D^+\pi^-$ final state (not shown) is of similar quality.

The FOCUS results for the broad states are for an unknown superposition of the D_0 plus feed-down from the broad D_1. Their fit parameters are tabulated in Table 1. The sample sizes for the four states are around 10K events each. The narrow state parameters are determine in reasonable agreement with previous work with uncertainties which are smaller or the same as those in PDG03. The broad states are fit for the first time with parameters in sensible agreement with similar new results from BELLE[18].

FOCUS also has reported a confirmation of the $D_{sJ}^+(2317)$ (shown in Figure 3) observed first by BABAR [1] and decay modes for several of the excited D_s states including $D_{sJ}^+(2573) \rightarrow D^0K^+$, and a first observation in $D_{sJ}^+(2573) \rightarrow D^+K_s^0$, shown in Figure 4. All of these observations are consistent with the known properties of these states from the PDG.

4. SELEX Results

After the discovery of the new narrow states in the D_s system in the summer of 2003 one of the SELEX groups was motivated to search for additional states in SELEX data. The ambitious approach they undertook was to look in the final state with a D_s^+ and an η^0 meson, in analogy with the $D_s^+\pi^0$ final states where BABAR and CLEO had already succeeded. Attempting to use η^0's in a multi-hadronic environment like SELEX's, where the mean charged and photon

Table 1. Measured masses and widths for narrow and broad structures in $D^+\pi^-$ and $D^0\pi^+$ invariant mass spectra. The first error listed is statistical and the second is systematic. Units for the masses and widths are MeV/c^2.

	D_2^{*0}	D_2^{*+}	$D_2^{*+} - D_2^{*0}$	$D_0^{*0}(j_l = \frac{1}{2})$	$D_0^{*+}(j_l = \frac{1}{2})$
Yield	$5776 \pm 869 \pm 696$	$3474 \pm 670 \pm 656$		9810 ± 2657	18754 ± 2189
Mass	$2464.5 \pm 1.1 \pm 1.9$	$2467.6 \pm 1.5 \pm 0.76$	$3.1 \pm 1.9 \pm 0.9$	$2407 \pm 21 \pm 35$	$2403 \pm 14 \pm 35$
PDG03	2458.9 ± 2.0	2459 ± 4	0 ± 3.3		
Belle03	2461.6 ± 3.9			2308 ± 36	
Width	$38.7 \pm 5.3 \pm 2.9$	$34.1 \pm 6.5 \pm 4.2$		$240 \pm 55 \pm 59$	$283 \pm 24 \pm 34$
PDG03	23 ± 5	25^{+8}_{-7}			
Belle03	45.6 ± 8.0			276 ± 66	

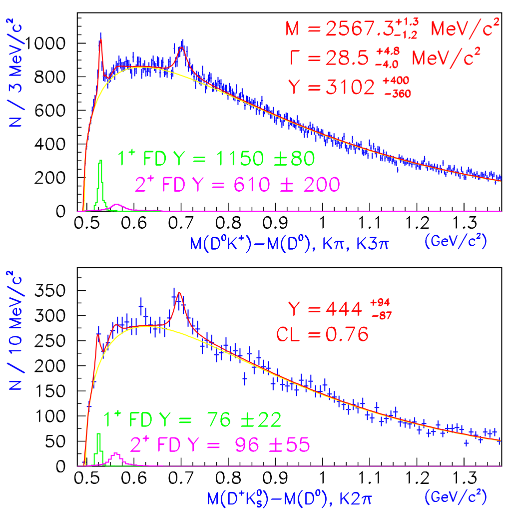

Figure 4. FOCUS $D_{sJ}^+(2573)$ signals

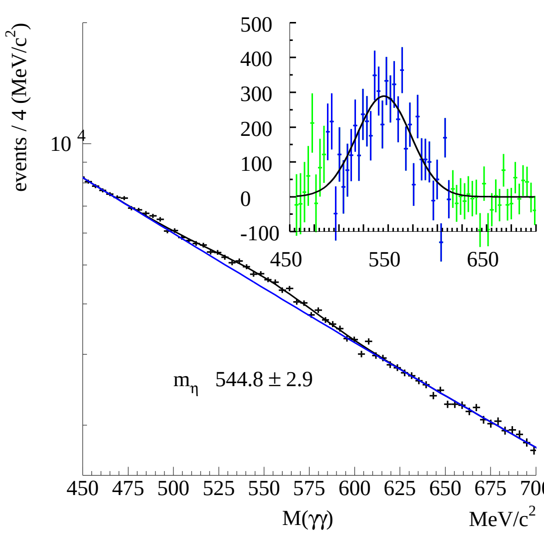

Figure 5. $M(\gamma\gamma)$ distribution for photon pairs in the η^0 mass region from 0.1% of the SELEX data sample. The inset shows the background subtracted η signal. The dark points indicate the η signal region.

multiplicity are each about 10, is challenging. The η^0 is reliably reconstructed (figure 5) but with a signal to noise ratio of only 5% due to the large number of photon combinations.

Nonetheless when this η^0 sample is combined with SELEX's well studied D_s sample [13] the mass difference plot shown in Figure 6 emerges. In the $D_s^+\eta$ decay mode we observe an excess of 46 events with a significance of 6.2 σ at a mass of 2635.4 ± 3.3 $\mathrm{MeV/c^2}$. The combinatoric background is assessed by combining the D_s candidates from each event with the η^0 candidates from 25 other events. As shown in Figure 6 this background describes everything seen save the signal peak.

Noting that a state at 2635 $\mathrm{MeV/c^2}$ is well above D^0K^+ threshold we searched in that final state for a confirming signal. As seen in Figure 7 along with the long known $D_{sJ}^+(2573)$ there is a corresponding peak of 21 events with a significance of 5.3 σ at 2631.5 ± 2.0 $\mathrm{MeV/c^2}$ in the D^0K^+ decay mode. From this decay mode the width of this state is $< 17\,\mathrm{MeV/c^2}$ at 90% confidence level. The relative branching ratio $\Gamma(D^0K^+)/\Gamma(D_s^+\eta^0)$ is 0.14 ± 0.06. The mechanism which keeps this state narrow is unclear. Its decay pattern is also unusual, being dominated by the $D_s^+\eta^0$ decay mode.

SELEX has reported [14] the first observation of a charm-strange meson $D_{sJ}^+(2632)$ at a mass of $2632.5 \pm 1.7\,\mathrm{MeV/c^2}$ seen in two decay modes, $D_s^+\eta^0$ and D^0K^+.

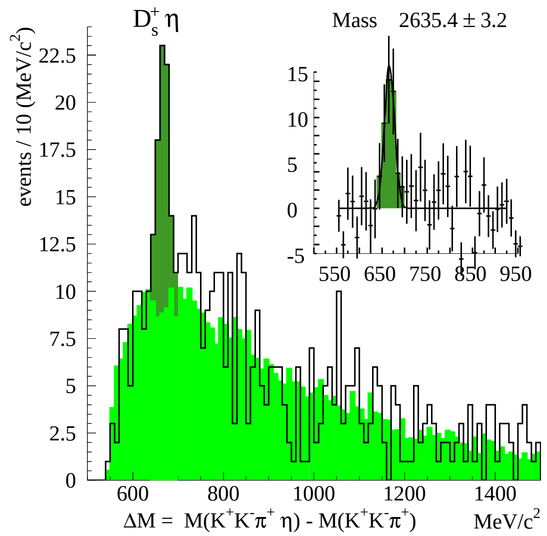

Figure 6. $M(KK\pi^{\pm}\ ^{\pm}\eta)$ - $M(KK\pi^{\pm}\ )$ mass difference distribution. The darker shaded region is the event excess used in the estimation of signal significance. The lighter shaded region is event-mixed combinatoric background. The inset shows the difference of the two with a Gaussian fit to the signal.

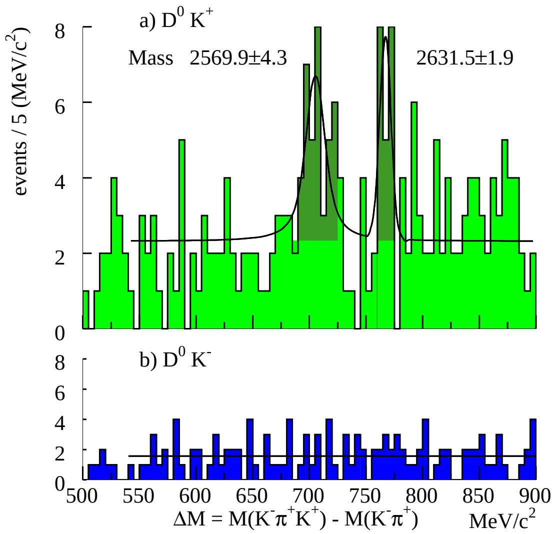

Figure 7. (a) D_s (2632) $\rightarrow$ D^0K^+ mass difference distribution. Charged conjugates are included. The shaded regions are the event excesses used in the estimation of signal significances. (b) Wrong sign background D^0 K^- events.

At the Photon-Lepton Conference this past summer BABAR reported [15] negative results in their search to confirm the $D_{sJ}^+(2632)$. This state is not produced copiously in e^+e^- production. Perhaps this state has a high J where e^+e^- production tends to be suppressed; perhaps SELEX is wrong [16]. Time will tell.

5. Conclusions

The heavy-light meson systems still require exploration and explanation. The model predictions are close to what has been observed but seem not to have predicted these system as well as the analogous models worked in the "onia". There is physics in this observation: we seem to need something more to postdict the spectroscopy and properties of these systems. Perhaps exotica has a role to play here. For my taste this isn't the first explanation we should invoke, but it could be the last.

There is a list of experimental questions left open as well. Are there more narrow states to be found? Can the $D_{sJ}^+(2632)$ observation be confirmed or have we (SELEX) made a mistake? Can we measure the quantum numbers of these states as opposed to assuming we know who they must be? How will all of this spectroscopy carry over into the really heavy-light systems with b quarks?

Spectroscopy has been for at least the last century the most important window into the structure of matter and the forces that bind it together. This work continues in that direction with no end in sight.

Acknowledgments

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